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13. ABSTRACT *(Maximum 200 words)*

Structures supported by a framework of inflated toroidal and cylindrical tubes would have relatively low weight and be easy to transport and erect. The tubes would be made of fabrics. Fabric composites have superior mechanical performance, such as high strength and low weight. In recent years, the development of textile structural composites has increased the need to investigate their behavior and effective properties. The properties can be controlled by changing the parameters, e.g., fiber orientation, fiber and matrix material properties, and fiber volume fraction. In this study, a survey of the research on the behavior and mechanical properties of textile composites of two common types, woven and braided, is presented. Various investigations, both analytical and experimental, are described. Elementary models, laminate theory models, and numerical (finite element) models are included in the review. Some programs that have been developed to calculate the mechanical properties of textile composites, such as TEXCAD and FABCAD, are discussed. The failure behavior of textile composites is also surveyed.

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Structural Engineering

A SURVEY OF RESEARCH ON THE BEHAVIOR AND MECHANICAL PROPERTIES OF TEXTILE COMPOSITES

by

Surjani Suherman

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Abstract

Structures supported by a framework of inflated toroidal and cylindrical tubes would have relatively low weight and be easy to transport and erect. The tubes would be made of fabrics. Fabric composites have superior mechanical performance, such as high strength and low weight. In recent years, the development of textile structural composites has increased the need to investigate their behavior and effective properties. The properties can be controlled by changing the parameters, e.g., fiber orientation, fiber and matrix material properties, and fiber volume fraction. In this study, a survey of the research on the behavior and mechanical properties of textile composites of two common types, woven and braided, is presented.

Various investigations, both analytical and experimental, are described. Elementary models, laminate theory models, and numerical (finite element) models are included in the review. Some programs that have been developed to calculate the mechanical properties of textile composites, such as TEXCAD and FABCAD, are discussed. The failure behavior of textile composites is also surveyed.

Introduction

In this study, a survey of some work on woven and braided textile composites is presented. The review starts with the research on analytical investigations including mathematical and numerical analysis. Some programs that have been developed to predict the mechanical properties of textile composites are also discussed. Besides that, some works use standard programs such as IDEAS or ABAQUS. Then, experimental investigations by many researchers are described. Another interesting subject, the failure behavior of textile composites, is presented. Finally, some studies of inflatable structures using these fabrics are reviewed.

Analytical Investigation

There are two common types of textile composites, woven and braided (Chou and Ko, 1989). Several types of woven fabric patterns are shown in Fig. 1. In Fig. 2 a triaxially braided pattern is shown. To examine the stiffness, strength, and thermal expansion of woven fabric composites, Ishikawa and Chou (1982a, 1983a,b,c) and Chou and Ko (1989) proposed three analytical models, i.e., the mosaic model, the fiber undulation model, and the bridging model (Fig. 3). The mosaic model simplified the composites by omitting the fiber continuity and undulation (crimp). By assuming constant strain and constant stress, this model was effective in predicting the thermal expansion and thermal bending coefficients. This model could also be used for woven hybrid composites (Ishikawa and Chou, 1982b). The fiber undulation model considered the continuity and undulation of the fibers and led to a softening in the in-plane stiffness. A slightly higher in-plane thermal expansion coefficient and the same thermal bending coefficient were obtained by this fiber undulation model compared to those obtained from the mosaic model. The bridging model was specifically developed to estimate the elastic behavior of satin weaves, where a fill yarn was interlaced with multiple warp yarns. This model simulated the load transfer among the interlaced regions in the satin composites. All models were two-dimensional and based on the classical laminate theory.

Yang et al. (1986) extended these models to predict the elastic properties of three-dimensional textile structural composites based upon classical laminated plate theory and the fiber inclination model. The idealized unit cell of the fiber inclination model treated all yarns as composed of straight segments oriented in different directions. However, the interaction among the yarns in the unit was not taken into account.

In another paper, Ishikawa and Chou (1983d) studied the nonlinear elastic behavior of woven fabric composites. Three types of nonlinearity were considered: the shear deformation of the fill threads, the extensional deformation of the pure matrix regions, and the transverse cracking of the warp regions. In order to evaluate the theoretical predictions of the elastic moduli of the fabric composites, some experiments were conducted (Ishikawa et al., 1985). Experimental results agreed with the theory for the eight-harness satin carbon/epoxy system, but not for the plain weave composites.

Another analytical solution was derived by Naik and Shembekar (1992) and Naik (1994) to predict the elastic properties of woven fabric composites. In a one-dimensional model, the actual fabric geometry was not considered and either an iso-stress or iso-strain condition was assumed. However, in a two-dimensional model, the actual yarn and fabric geometry was considered and the iso-stress and iso-strain conditions were again used. A comparison of the in-plane elastic moduli between the unidirectionally laminated composite and plain weave fabric composite was made by Shembekar and Naik (1992). In another paper (Naik and Shembekar, 1993), they also examined the elastic properties of mixed composites, formed by a combination of unidirectional laminates and woven fabrics. Of course, they found that the mixed composites offered higher elastic properties

than the equivalent unidirectional composites. The prediction of the off-axis elastic properties of plain weave fabric laminates was presented by Shembekar and Naik (1993). They used a 2-D woven fabric composite model and found that the off-axis Young's modulus and shear modulus of plain weave fabric laminates were higher than those for the corresponding unidirectional laminates, but the off-axis Poisson's ratio was lower. Naik and Ganesh (1995) also used the 2-D closed-form analytical method to predict the thermoelastic properties of 2-D orthogonal plain weave fabric composites.

Other approaches to predict the elastic properties of fabric composites have been proposed. Falzon et al. (1993) compared the capabilities of several techniques in predicting the stiffness of woven composites. There were three classes of models, i.e., elementary models, laminate theory models, and numerical models. Two elementary models were the Fabric Geometry Model and the Angle Ply Undulation Model, which relied on a three-dimensional generalized Hooke's Law approach. However, elementary models were unsuitable for a strength analysis. Laminate theory models were based on classical laminate theory, used by Ishikawa and Chou as mentioned before. Numerical (Finite Element) models could be used for stiffness and strength predictions of 2-D and 3-D models.

Byun and Chou (1989) also reviewed recent progress in the modeling of the thermo-mechanical behavior of textile structural composites, including 2-D hybrid and non-hybrid woven fabric depending on the types of fibers, 3-D braided composites, and 3-D angle interlock fabrics which provided through-the-thickness reinforcement by interlacing yarns in the transverse direction. The elastic properties of 3-D braided composites were analyzed based on the energy method and the fiber inclination model. The modified fiber inclination model was applied to study the 3-D angle interlock fabric composites.

Byun et al. (1991) analyzed two-step braided composites based on the lamination theory (for a micro-cell model) and the stiffness averaging method (for a macro-cell model). A two-step braided preform (Fig. 4) was composed of a set of straight axial yarns intertwined by braider yarns. Based on the macro-cell model, the effects of various braiding process parameters on the effective elastic properties were examined, such as the linear density ratio between axial and braider yarns, the pitch length of the braider yarns, the aspect ratio of the axial yarns, and the aspect ratio of the braider yarns. In another paper, Byun and Chou (1991) compared the mechanical properties of two-step and four-step braided composites (Figs. 4, 5) experimentally. Kostar and Chou (1994) described the simulation of two-step and four-step 3-D braiding processes. On the other hand, Soebroto and Ko (1989) presented an overview of the fabrication of 2-D braiding fabric.

Ma et al. (1986) determined the elastic properties of 3-D woven and braided textile composites based upon the concept of the fabric unit cell structure and the energy approach. The impregnated yarns (with matrix materials) were assumed as composite rods in the form of straight line segments. Based upon the interaction of yarns in two dimensions, the energy approach was formulated. Du et al. (1991) and Du and Ko (1993)

also used a unit cell approach in developing a mathematical model for analyzing the structural geometry of 3-D braided composites. In the latter paper, they demonstrated that two-step braiding was a special variation of 3-D four-step braiding.

Furthermore, the mathematical model for studying the tensile stress-strain relationship of woven fabrics was developed by Jianlian (1993). He used a nonlinear regression technique with an exponential function containing two parameters. To select the functions, he examined the tensile curves of samples. Keefe (1994) established a 3-D model of woven fabrics by treating a yarn as a solid model with a closed curve swept along a centerline path. The cross section of the individual yarn was assumed to be elliptical to give an approximation of the effect of compressibility on the yarns. Wei and Chen (1994) derived equations for calculating the bending behavior of plain woven fabrics in the warp or weft direction by adopting a nonlinear law.

Ning and Chou (1995) formulated a closed-form solution of the transverse effective thermal conductivity of woven fabric composites. The analytical solution was based upon the constituent material properties, fiber volume fraction, and fabric parameters. Dadkhah et al. (1995) modified laminate models to include the tow waviness for predicting the in-plane elastic properties of triaxially braided composites.

Pochiraju and Chou (1996) presented analytical models to estimate the elastic stiffness and strength of 3-D woven and braided composites based on the geometric modeling of the fiber microstructure and the fiber and matrix material properties. They denoted the repeated geometric structures as Macro-cells. The geometry within macro-cells was divided into unit cells that described the path of a single fiber yarn. Then, the yarn path was modeled with a function approximation such as a sine function for the undulation.

The unit cell continuum model, presented by Foye in 1990, was based on the principles of finite element analysis using heterogeneous hexahedral elements to predict the elastic properties of textile composites. However, sometimes this introduced mathematical instabilities in the solution if the stiffnesses of the fibers and matrix were different. Later, Gowayed et al. (1996) modified this model based on a micro-level homogenization at the integration points using a self-consistent Fabric Geometry Model. The fibers and the matrix were treated as a set of composite rods having various spatial orientations. Fiber architecture and material properties were related to the global stiffness matrix of the composite through micromechanics and a stiffness averaging technique.

Paumelle et al. (1991) analyzed the stresses induced inside woven composite microstructures by using the technique of homogenizing periodic media. They used double homogenization, i.e., homogenizing the properties of the yarn (fiber and resin) and homogenizing the properties of the fabric (yarn and resin). Dasgupta and Bhandarkar (1994) developed a 3-D finite element by using a two-scale homogenization theory to predict the linear thermomechanical properties of plain weave composites. The microscale was related to the characteristic dimension of the unit cell and the macroscale

was related to the gross overall dimension of the structure. Then, the volume averaging of stress and strain was used to calculate the homogenized effective overall properties of the composites. The elements were modeled as eight-noded, three-dimensional, linear, isoparametric elements along with some wedge and tetrahedral elements at the yarn-matrix interfaces.

Ko (1986) presented a geometric model for 3-D braided composites using the concept of average cosine for presenting the yarn orientation to examine the tensile strength and modulus. Ko and Pastore (1985) also studied the structure and properties of 3-D fabrics formed by an irregular braiding process and developed a computerized design and analysis of braided preforms. Soebroto et al. (1990) established design equations for braided composites by relating the braiding process parameters and yarn geometry to the braid geometry.

Sankar and Marrey (1993) obtained a finite element model of the unit cell of textile composites to predict the flexural stiffness properties. They used a beam model similar to the 1-D fabric strip model presented by Ishikawa and Chou (1983a). Three linearly independent deformations, i.e., pure extension, pure bending, and pure shear, were applied to the unit cell. Special constraint elements were used to apply periodic boundary conditions on the end faces of the unit cell.

Dastoor et al. (1994) developed a program called Fabric Computer Aided Design (FABCAD) to analyze uniaxial and biaxial load-deformation behavior of plain woven fabrics. The yarns were assumed to be homogeneous, weightless, frictionless, and undeformed by shear forces, and to have circular sections which did not deform under external forces. However, they had finite bending rigidity and were linearly extensible. Naik (1994a,b, 1995, 1996) also established a computer code called Textile Composite Analysis for Design (TEXCAD) to analyze a wide variety of fabric reinforced woven and braided composites, including plain weave, 2-D braided, 2-D triaxial braided, and 3-D multi-interlock braided composites. A micromechanics analysis that discretely modeled the yarn architecture within the textile repeating unit cell (RUC) predicted the overall thermal and mechanical properties, damage initiation and progression, and strength of woven and braided composites. An iso-strain state assumption within the repeating unit cell was applied. For the input, the material parameters such as yarn size, braided angle, yarn crimp, and yarn spacing were needed. He found that the in-plane properties varied significantly with the braid angle, and the strength decreased with increasing the braid angle or the axial yarn crimp angle. Masters et al. (1995) used this TEXCAD program to examine the mechanical properties of 2-D triaxially braided composites. A parametric study was conducted on two categories, i.e., primary braid parameters (yarn size, braid angle, axial yarn content) and secondary braid parameters (axial yarn spacing, braid yarn crimp angle, zero degree yarn crimp angle). Zhang et al. (1996) noted that the braid parameters were related to one another.

Raju and Wang (1994) used classical laminate theory models to analyze the elastic properties of woven fabric composites. In this study, they included the resin

properties in the model. The undulation of both the warp and fill yarns was treated as they were in the unit cell; there was no assumption to simplify the analysis. Whitcomb and Woo (1994) developed the direct stiffness method for finite element analysis of textile composites. They also proposed a technique for calculating the stiffness matrix for a reduced substructure.

Marrey and Sankar (1995) and Sankar and Marrey (1995) established micromechanical models for predicting the stiffness and strength properties of textile structural composites. They developed a finite element code, called $\mu TE\chi$-10 (microtech-10), to predict the textile composite properties. Also, they developed another code, called $\mu TE\chi$-20 (microtech-20), implementing the Selective Averaging Method. This method used an approximate analytical method, in which both stiffness and compliance coefficients were averaged selectively depending on a more realistic assumption of either iso-stress or iso-strain. They assumed a repeating unit cell shape of the composite as a rectangular hexahedron. Cox et al. (1994) and Cox (1995a,b) presented a binary model (a finite element model) of 3-D woven composites to calculate the elastic constants, strength, notch sensitivity, and fatigue life by using two types of elements. The yarns were modeled using two-node line elements and the rest of the medium by eight-node solid elements. They also applied Monte Carlo simulations to predict failure mechanisms in angle and orthogonal interlock woven composites under monotonic and fatigue loading.

Chapman and Whitcomb (1995) examined the effect of assumed tow architecture on the predicted moduli and stresses in plain weave composites by using 3-D finite elements. They assumed a sinusoidal yarn path and a lenticular cross section. They studied two types of tow architectures, the translated architecture by keeping the section vertical along the tow path and the extruded architecture by keeping the section perpendicular to the tow path. At a high waviness ratio there was a significant difference between them. Hewitt et al. (1995) established a computer modeling of woven composites. The model, providing a 3-D representation of any single layer weave geometry, comprised a series of blocks containing a warp and weft crossover area. When the blocks were assembled in the correct orientation, they joined together to form a weave pattern.

Pastore et al. (1995) developed Textile Geometry Models for characterizing the geometry of yarns within the composites. Using this model in a 3-D finite element analysis, Glaessgen and Griffin (1995a,b) investigated the displacement, stress, strain, failure parameters, and effects of boundary conditions on the response of woven textile composites. They used the IDEAS and ABAQUS programs. Thermal and mechanical loading were also considered. Shkoller and Hegemier (1995) derived the governing equations of plain weave composites by using convergence results developed for a periodic function. Whitcomb et al. (1995) evaluated the global and local stresses of textile composites by using the boundary model displacement and forces from the global analysis to determine the appropriate loading conditions for a refined local model. They

applied a finite element model. Homogenized engineering properties were utilized to obtain the global solution, but they gave significant errors in the prediction, especially at the boundaries.

Lei et al. (1988) used a finite cell method to analyze the mechanical behavior of 3-D braided composites. In this study, they treated the unit cell as a space-truss structure. This method was based on the principle of virtual work and structural truss analysis. Branch et al. (1996) established a 3-D tow inclination model to calculate the elastic constants of 2-D and 3-D woven and braided composites based on the oriented inclined tows and interstitial matrix. They wrote a program called Fortran Computer Code TowInc-3D for the analysis. The elastic constitutive matrix of the composite was derived from the 3-D stress transformation and the iso-strain condition.

Recently, Okumura et al. (1995) discussed an optimum design method of a woven structure of 3-D fabric composites by combining genetic algorithms and finite element analysis. The objectives of the optimum design were minimization of the density of 3-D composites and maximization of the stiffness or strength of 3-D composites for several loading directions.

Experimental Investigations

Beside analytical work, many investigations of textile composites included experiments. Simonds et al. (1988) measured the tensile and compressive strength and stiffness of braided composites experimentally. They also determined the fatigue life and stiffness of the material, subjected to fully reversed fatigue loading. Warren (1990, 1992) and Ericksen et al. (1992) investigated the force-deflection relations of plain woven Kevlar fabric experimentally under uniaxial loading. During initial loading the response was dominated by yarn bending, but for large loads the response was dominated by yarn stretching.

Masters et al. (1993) investigated the mechanical properties of 2-D triaxial braided composites experimentally. Minguet (1995) compared the mechanical properties between unidirectional composite tape laminates and 2-D triaxial braided composites based on the experiments. Results showed that the longitudinal modulus of both material forms was quite similar, but that the transverse modulus of the braids was lower. However, a very significant increase in open-hole and filled-hole tension strength was observed for the braids compared to the unidirectional laminates.

Fujita et al. (1993) discussed the tensile properties and fracture behavior of woven composites by experiments. Shivakumar et al. (1995) studied the compression strength of 3-D triaxially braided and orthogonally woven composites experimentally. They found that the compression strength was highly sensitive to the axial tow misalignment and less sensitive to the off-axis tow orientation. Masters (1996a) also established a

compression test method for 2-D triaxially braided composites. In another paper (Masters, 1996b) he proposed a criterion to select the strain gages for the tests.

Ifju (1995a) investigated 2-D triaxial braids and 3-D woven textile composites experimentally by using Moiré Interferometry, an optical experimental technique characterized by high in-plane displacement sensitivity, full-field capabilities, high spatial resolution, and high signal to noise ratio. By this technique, the stiffness, strength, shear deformation, and damage mechanisms of the textile composite could be determined. In Ifju (1995b), he examined the shear response (including the shear stress-strain curve, the shear modulus, and the shear strength) of 2-D braided and 3-D woven textile composites by using a compact shear specimen and a shear gage in the experiments.

Swanson and Smith (1995) presented experimental results of the stiffness and strength of carbon/epoxy 2-D triaxial braided composites under general conditions of biaxial stress loading, involving both compression-compression and tension-tension biaxial tests. Wang et al. (1995) also focused on the experimental study of the mechanical properties of woven fabric composites under uniaxial tensile, flexural, compressive, and short beam shear actions. An experimental investigation of the thermal conductivity of woven textile composites was conducted by Gowayed and Hwang (1995). They also used an analytical approach based on the Fabric Geometric Model, in which the fibers and the matrix were treated as a set of composite rods having various spatial orientations. Avva et al. (1996) presented mechanical test procedures, test data, and results of compression and textile properties of 3-D braided composites.

Failure Behavior

Failure mechanisms of textile composites were also studied by many researchers. Naik et al. (1991) studied the failure behavior of woven fabric composites with and without a hole. They found that the ultimate failure was due to fiber breakage. On the other hand, the failure behavior of 2-D woven fabric composites under in-plane shear loading was examined by Naik and Ganesh (1994) and Ganesh and Naik (1995). Chou and Chen (1992) investigated the flexural and shear fracture behavior of 3-D woven composites. Later, Wang and Zhao (1995) studied the effects of fiber type, fabric weave pattern, and additions of microfibers to the matrix on the interlaminar toughness of 2-D woven composites. They used double cantilever beam tests under mode I loading. It was found that the weave patterns of fabrics exhibited a strong influence on the interlaminar fracture behavior, and that the addition of the microfibers to the epoxy matrix could improve the interlaminar fracture resistance significantly.

Blackketter et al. (1993) presented a method for describing damage propagation in woven fabric composites subjected to tension or shear loading by using a 3-D finite element model. Burr and Morris (1995) also studied the characterization of damage processes of 2-D braided composites subjected to both static and fatigue loading. They tested both notched and unnotched specimens. Whitcomb and Srirengan (1995, 1996)

also simulated the progressive failure of plain weave composites by using a 3-D finite element analysis subjected to in-plane extension. The behavior was sensitive to the quadrature order, mesh refinement, and material degradation model.

Cox et al. (1992, 1994) investigated the failure mechanisms of 3-D woven composites with angle interlock reinforcement under monotonic loading (tension, compression, and bending). The mechanisms of failure were determined by a combination of optical microscopy, Moiré Interferometry, stereoscopy, and digital image comparison. Kink band formation in compression, tow rupture, pullout in tension, and combinations of these in bending were the common failure mechanisms. The materials exhibited a great potential for damage tolerance and notch insensitivity. In another paper, Cox et al. (1996) concentrated on the tensile failure of 3-D woven composites. The key mechanism was very strong friction or lockup that couples sliding and broken tows to the surrounding composites. Lockup was the product of the geometrical irregularity of straight tows and clamping compressive stresses generated by through-the-thickness reinforcement.

Adams et al. (1995) investigated the interaction between neighboring fabric layers, called nesting, of 2-D woven composite laminates. Three idealized nesting cases, i.e., stacked, split-span, and diagonal cases (Fig. 6), were analyzed by using a 2-D plane strain finite element model under static compression loading. In general, all three nesting cases produced a reduction in the strength and strain of the composites.

Fang et al. (1988) showed that the reduction of the compressive strength and strain of braided and woven composites subjected to low velocity impact was not as sensitive as for unidirectional laminates. Portanova (1995) also evaluated impact response of textile composites, including impact damage resistance and impact damage tolerance. Three different textile composite material forms were tested: stitched and unstitched uniweaves, 2-D braids, and 3-D woven. Also, three different through-the-thickness weave types were evaluated: angle interlock, orthogonal interlock, and layer-to-layer interlock (Fig. 7). Kang and Lee (1994) studied the mechanical and impact-resistant properties of stitched woven laminate composites. They showed that the stitching improved the tensile, flexural, and impact-resistance properties. The effects of the through-the-thickness stitching on the impact response of textile laminates were also studied by Sankar and Sharma (1995).

Fleck et al. (1995) examined the compressive failure mechanisms of laminated and woven composites for both notched and unnotched specimens. They found that the dominant failure mechanism was plastic micro-buckling of the load-bearing axial tows. Woven composites had a high damage tolerance and a low compressive strength, due to the large amount of fiber misalignment. Norman and Anglin (1995) and Norman et al. (1995, 1996a,b) investigated the tensile strength and failure mechanisms of unnotched and notched 2-D triaxial braided composites, including the effect of notch size and notch position. The damage initiation stress decreased with increasing braid angle. Marrisen et al. (1995) examined the notched strength of thermoplastic woven fabric composites.

As mentioned by Brookstein (1990), interlocked fabrics could increase interlaminar strength properties of braided and woven composites. Whitney and Chou (1989) developed a model to predict the elastic properties of 3-D angle interlock textile composites by utilizing straight yarn segments and micro-cells in a lamination analogy. Crane and Camponeschi (1986) and Macander et al. (1986) described mechanical properties of the through-the-thickness fiber-reinforced composites experimentally and analytically. The analytical model was based on classical lamination theory to predict the extensional stiffnesses. Hartfrant et al. (1995) and Jackson and Portanova (1995) also investigated the through-the-thickness properties of woven composites. Farley (1992) identified a mechanism that contributed to the reduction of compression strength of composite materials with through-the-thickness reinforcements experimentally. Then, Adanur et al. (1995) proposed that the properties in the through-the-thickness direction of 3-D composites could be improved by reinforcing the transverse direction.

Inflatable Structures

Steeves (1979) studied the use of pressurized arches for a framework for a tent. There were three types of concepts, i.e., crossed-arch concept, leaning-arch concept, and arch-and-purlin concept. Hesselink (1990) discussed the use of polyester duck materials for the framework. Furthermore, FTL/Happold (1992, 1994) analyzed the optimization of the fabric for the air-inflated tubes, including the configuration and structural applications. The interaction between the tubes and the tent skin was studied. The bending moment could be carried with the tent skin taking the tension and the tubes taking the compression. However, the skin would also have the effect of restraining the pressurized arches against buckling. These reports also considered some other features such as temperature and atmospheric pressure effects, safety from bursting or venting, pressure loss, stress concentrations, methods of inflation, and weight optimization. In his book, Firt (1983) mentioned that the mechanical properties of industrial fabrics depended primarily on the way the stress was applied to the fabric. Also, the strength of the fabric should be reduced due to a biaxial loading.

Archer (1986) performed numerous tests on braided tubes involving tension, compression, internal pressure, and tension. Sainsbury-Carter (1987) discussed the design, fabrication, and testing of composite tubes made from biaxial braid, triaxial braid, and a combination of unidirectional carbon tape and biaxial braid. On the other hand, Yokoyama et al. (1989) investigated the behavior and failure modes of braided tubes under tensile and bending load experimentally. The braided structure was effective in preventing failure propagation and increased the deformation energy.

Remarks

Various investigations, analytical and experimental, have been reviewed. The behavior in the failure mechanisms studied by many researchers was also discussed. However, the complexity of textile composites makes it difficult to model the fabrics, and further investigations of textile composites are needed.

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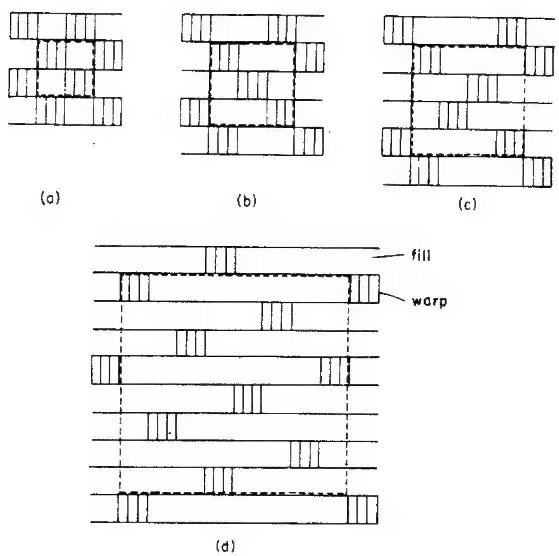


Fig. 1 Several types of woven fabric patterns: (a) plain weave; (b) twill weave; (c) 4 harness satin; and (d) 8 harness satin (Ishikawa and Chou, 1982a)

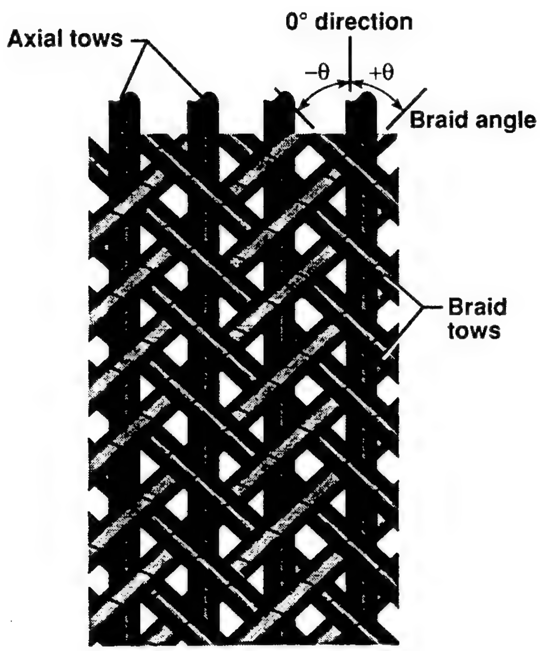
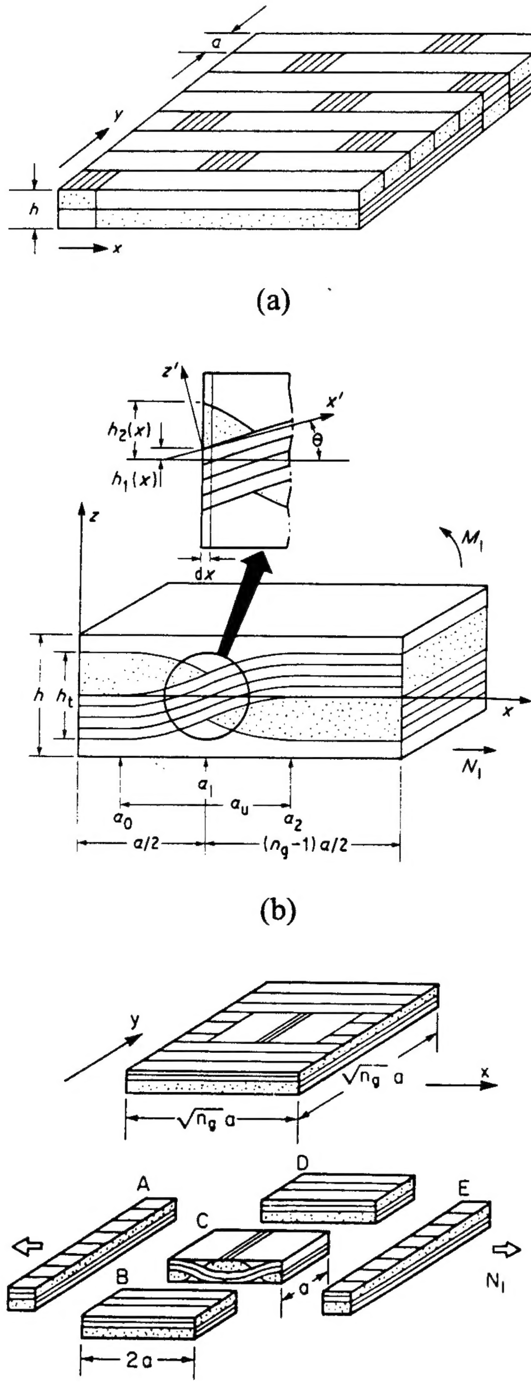


Fig. 2 Triaxial braid pattern (Masters et al., 1993)



(a)

(b)

(c)

Fig. 3 Three analytical models: (a) mosaic model; (b) fiber undulation model; (c) bridging model (Ishikawa and Chou, 1982a, and Ishikawa et al., 1985)

Fig. 4 Two-step preform
(Kostar and Chou, 1994)

Fig. 5 Four-step preform
(Kostar and Chou, 1994)

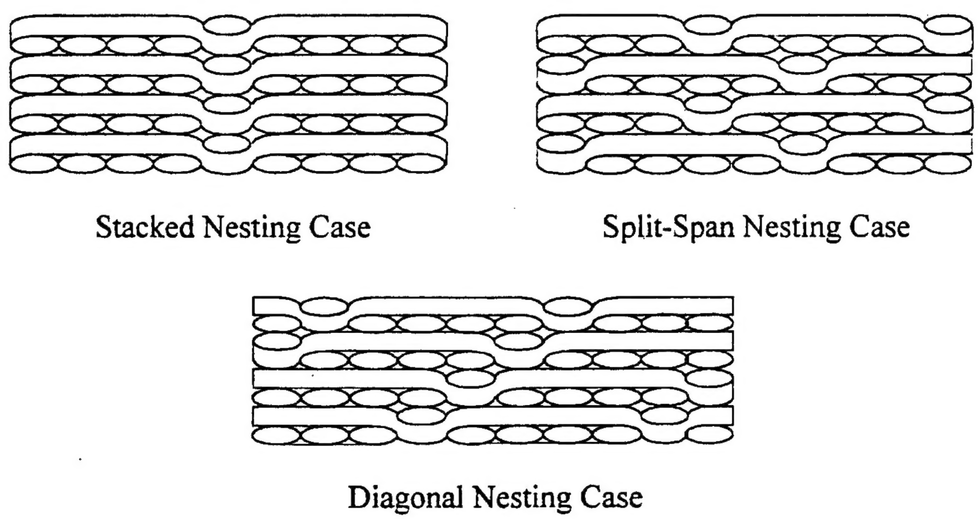


Fig. 6 Three idealized nesting cases (Adams et al., 1995)

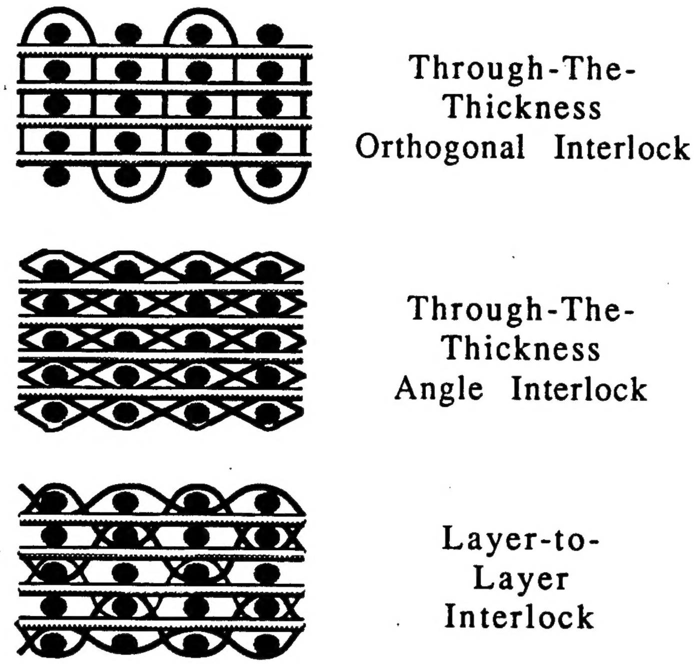


Fig. 7 Three different through-the-thickness weave types: (a) orthogonal interlock; (b) angle interlock; (c) layer-to-layer interlock (Portanova, 1995)